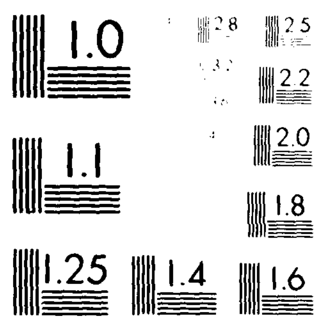
AD-A090 398 ARMY RESEARCH AND TECHNOLOGY LABS HAMPTON VA STRUCTU--ETC F/G 1/3
ON THE USE OF ACTIVE HIGHER HARMONIC BLADE PITCH CONTROL FOR HE--ETC(U)
JUN 80 C E HAMMOND, J E CLINE

UNCLASSIFIED NL

1 OF 1

AD A
090398

END
DATE
FILMED
11-80
DTIC


1.0
2.8
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

LEVEL II

ON THE USE OF ACTIVE HIGHER HARMONIC BLADE PITCH CONTROL FOR HELICOPTER VIBRATION REDUCTION

JUN 1980

*CHARLES E. HAMMOND, PhD
JOHN H. CLINE
STRUCTURES LABORATORY
UNITED STATES ARMY RESEARCH AND TECHNOLOGY LABORATORIES
(AVRADCOM)
NASA LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA 23665

Vibration levels have been a problem in helicopters since their inception. The reason for this lies in the method whereby the helicopter generates its lift, namely, the rotor system. As the rotor blades rotate they encounter a continuously changing aerodynamic environment which results in a continuously changing environment which results in a continuously changing aerodynamic loading on the blades. This changing environment is repeated on each revolution of the rotor. Hence, the rotor develops aerodynamic loads which are oscillatory in nature. These oscillatory loads are transferred directly to the helicopter airframe through the mechanical connection of the rotor to the airframe, i.e., the rotor-shaft/transmission attachment. Oscillatory loads are also transmitted to the airframe by impingement of the rotor wake on the upper portion of the airframe, but the mechanically transferred loads are in most cases much more significant than the aerodynamically transferred loads.

Because of the symmetrical placement of blades in a rotor, the oscillatory loads felt by the airframe occur at frequencies which are multiples of the number of blades times the rotational frequency of the rotor. For example, if Ω is the rotational speed for a four-bladed rotor, the oscillatory loads would occur at frequencies of 4Ω, 8Ω, 12Ω, etc. Conventionally, these frequencies are denoted as 4P, 8P, 12P, etc. The oscillatory loads which occur at the first harmonic of the blade passage frequency, i.e., 4P for a four bladed rotor, are the loads of primary concern in any helicopter vibration reduction program. The reason for this is that these loads are generally significantly higher than the higher frequency loads, and as a result tend to mask the influence of the higher frequency loads. There have been cases reported, however, where the higher frequency loads became more significant when the first harmonic loads were reduced, e.g., reference 1.

Past efforts to reduce the vibration levels in helicopters have employed methods such as airframe tuning to avoid resonance of the structural frequencies with the frequencies of the oscillatory loads (ref. 2) and application of vibration control devices such as tuned vibration absorbers (ref. 3, 4), and vibration isolators (ref. 5). These approaches have been successful in the sense that the vibration levels on current generation helicopters are about one-half the levels which were achievable on previous generation machines. These lowered vibration levels are a result of a considerable amount of dedicated research and trial and error development of vibration control devices conducted primarily by the helicopter industry.

The vibration control devices, while successful in reducing vibration levels, add a significant amount of weight to the aircraft. The weight penalty on current helicopters which can be attributed directly to vibration control devices amounts to about two percent of the aircraft gross weight. Although this is the generally accepted industry method of presenting the weight penalty, it is more significant from a user point of view to note that this weight penalty amounts to about fifteen percent of the aircraft payload. Thus, if vibration reduction can be achieved at lower weight penalties, significant increases in the aircraft useful payload can result.

It is the purpose of this paper to discuss an approach to vibration control different from the vibration control devices mentioned above, which depend to a large degree on the addition of mass for their effectiveness. This approach, which will be referred to as higher harmonic control (HHC), is aimed at altering the aerodynamic loads on the rotor before they are transferred to the airframe. This is in contrast to the vibration control devices discussed earlier which attempt to deal with the oscillatory loads after they have been generated. Higher harmonic control, as will be discussed later, is a method whereby the aerodynamic loading on the blade is tailored in such a way that the vibratory loads transferred to the airframe are minimized. Preliminary design studies by Hughes

(176)

Helicopters (ref. 6) have indicated that weight penalties on the order of 0.5 percent of gross weight are achievable with the higher harmonic control concept.

SYMBOLS

J	Magnitude of optimal control penalty function
T	Transfer matrix relating higher harmonic inputs to vibratory responses
W_Z	Matrix of response weights
W_θ	Matrix of control weights
Z	Column of vibratory responses
Z_o	Column of baseline vibratory responses (without higher harmonic control)
θ	Column of higher harmonic inputs

Superscripts

T	Transpose of a matrix
$\hat{}$	Estimated value from Kalman filter
$*$	Optimum higher harmonic inputs

HIGHER HARMONIC CONTROL CONCEPT

Higher harmonic control is achieved by superimposing non-rotating swashplate motions at the blade passage frequency (4P for a 4 bladed rotor) upon the basic collective and cyclic flight control inputs. The frequency of the inputs is picked at the blade passage frequency because this is the frequency of the loads which are to be suppressed. The amplitude and phase of the higher harmonic inputs are chosen so as to achieve minimization of the responses being controlled.

This approach to control vibratory loads has been the subject of a number of recent wind tunnel investigations, e.g., references 7, 8, and 9. These investigations, which were each conducted on significantly different types of rotor systems, all showed that higher harmonic control was successful in reducing the vibratory loads transmitted by the rotor to the airframe. These tests further indicated that the amplitude of higher harmonic blade pitch inputs required to achieve the desired reductions was small; on the order of one degree for the conventional helicopter flight envelope.

The primary parameters which determine the success of the higher harmonic inputs in reducing the vibratory loads are the amplitudes and phases of the various inputs. In the references 7, 8, and 9 these inputs were determined through trial and error testing. This trial and error approach is satisfactory if one is using a single input to control a single response. However, when three controls are used to control one or more responses, then the number of possible combinations of inputs becomes too numerous for the trial and error approach to be successful. Furthermore, if the higher harmonic control technique is to be applied to production helicopters then some systematic means must be available to determine, automatically, the required inputs. The means for automatically determining the higher harmonic inputs constitutes a closed loop active control system.

Active Control System

The active control system to be discussed here is the approach which has been taken at the Structures Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM). Other researchers in the field, notably the Boeing Vertol researchers (reference 8) are pursuing somewhat different approaches. A schematic of the active control system employed in obtaining the results reported herein is shown in figure 1.

In this case a four-bladed rotor wind tunnel model (to be discussed later) was used and the 4P higher harmonic inputs were used to control the 4P vibratory responses in vertical force, pitching moment, and rolling moment. In figure 1, the vibratory responses from the model (containing all the harmonics) are input to an electronic control unit (ECU). The ECU actually performs two separate functions, the first of which is to extract from the total vibratory response signals the amplitude and phase of the 4P contribution, since it is this contribution which is to be minimized. The ECU contains an analog implementation of a demodulation scheme which provides the sine and cosine components (from which the amplitude and phase may be determined) of the 4P responses in real time.

178

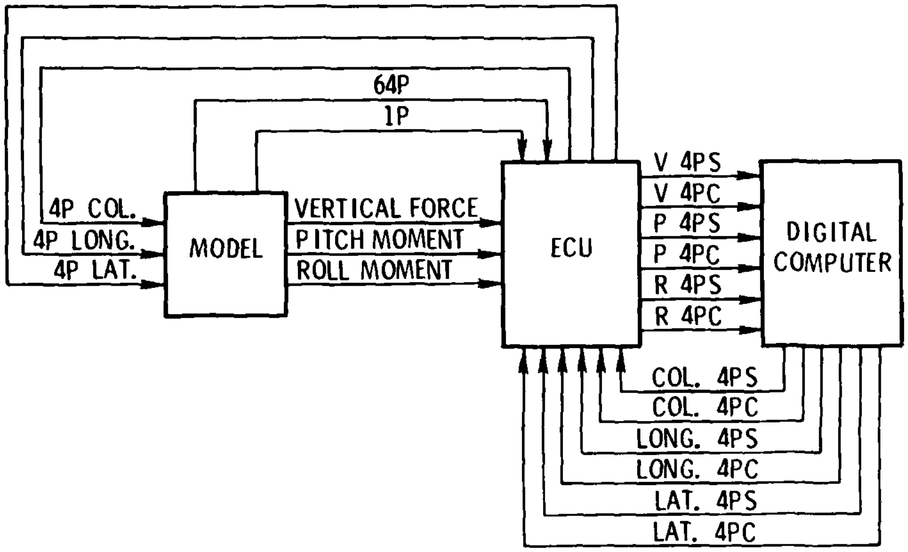


Figure 1. Block diagram of closed loop higher harmonic control system.

Figure 2. Aeroelastic Rotor Experimental System (ARES) installed in the Langley Transonic Dynamics Tunnel.

The sine and cosine components of the 4P responses are passed from the ECU to a digital computer which contains the software for the control algorithms. The nature of the control algorithms will be discussed in a subsequent section. The control software makes use of the measured responses to previous 4P higher harmonic inputs to determine the "optimum" higher harmonic inputs. The sine and cosine components of these "optimum" inputs are output from the computer as d.c. voltages which are passed to the ECU. The ECU then performs its second function which is to convert the d.c. voltages from the computer to 4P oscillatory analog signals having the correct amplitude and phase to drive the control system servos. The model then responds to these inputs and the control loop begins again.

The 1P and 64P signals shown on figure 1 are timing signals used by the ECU in extracting the 4P components of the responses.

Control Algorithms

The control algorithms employed in the program make use of digital optimal control theory (ref. 10). In implementing the theory, it is assumed that the 4P system response may be described by the following equations

$$\{Z\} = \{Z_o\} + [T]\,\{\theta\} \tag{1}$$

Note that these equations constitue a static linear representation. The equations state that the system 4P response is made up of a baseline response plus a response which is related to the 4P inputs by a transfer matrix. Thus, if the number of responses is the same as the number of inputs and if the baseline responses and transfer matrix are known, then a set of 4P inputs could be found which would null the 4P responses.

The first portion of the control strategy is thus to determine the baseline response and the transfer matrix. Since it is undesirable to turn the control system off to measure the baseline response, and since information about the system is available from past HHC inputs and the resulting responses, an identification algorithm is used to determine Z_o and T. The identification algorithm used is the Kalman filter (ref. 11). This algorithm may be thought of as a generalized form of a least-squares algorithm which accounts for the fact that the measured responses may be contaminated by noise and the transfer matrix mav be changing with time.

(180)

Once the baseline responses and the transfer matrix are known, the "optimum" outputs are determined as those inputs which will minimize the performance index

$$J = Z^T W_Z Z + \theta^T W_\theta \theta \tag{2}$$

If it is assumed that the transfer matrix is known without error, then the inputs which minimize the above performance index are given by

$$\theta^* = -[\hat{T}^T W_Z \hat{T} + W_\theta]^{-1} [\hat{T}^T W_Z \hat{Z}_o] \tag{3}$$

Note from equation (3) that if the response weighting matrix, W_Z, is the identity matrix and the control weighting matrix, W_θ, is zero, then the result from equation (3) is the same as solving equation (1) directly for the inputs which will give zero responses. The weighting matrix on the responses allows one to place more emphasis on reduction of some of the responses than others. The control weightings allow one to limit the amplitude of controls allowed.

The Kalman filter used in estimating the baseline responses and transfer matrix is a recursive algorithm and thus each new measurement of the responses leads to an updated estimate of the baseline responses and transfer matrix. With each update of these parameters, updated "optimum" inputs are calculated and applied to the rotor control system, and the cycle begins again. This control system is adaptive in that the estimates of the parameters used in the model, equation (1), are continuously updated and the updated parameter estimates are used to determine the optimal inputs.

The control algorithms are executed very quickly by the computer and permit updating the optimal control solution every revolution of the rotor. The algorithms would actually permit more rapid updating of the solutions, but it is felt that once-per-revolution updating is sufficient to accommodate the most rapid changes in flight conditions which might be experienced by a helicopter.

DESCRIPTION OF MODEL AND TESTS

The basic wind tunnel model used in this investigation was the Structures Laboratory Aeroelastic Rotor Experimental System (ARES) shown in figure 2. This model is the successor to the model described

191

in reference 12, and it is used for aeroelastic investigations of model scale rotor systems. These investigations are conducted in the Langley Transonic Dynamics Tunnel (TDT).

The TDT is a continuous-flow tunnel with a slotted test section and is capable of operation over a Mach number range up to 1.20 at stagnation pressures from .01 to 1 atmosphere. The tunnel test section is 4.9 m square with cropped corners and has a cross sectional area of 23 m^2. Either air or Freon-12 may be used as a test medium in the TDT. For this investigation, Freon-12 at a nominal density of 3.09 Kg/m^3 was used as a test medium. The advantages of using Freon-12 as a test medium for aeroelastic model testing have been discussed in references 13 and 14.

The ARES is powered by a 35 kw variable frequency synchronous electric motor connected to the rotor shaft through a belt-driven, two-stage reduction system. The model pitch attitude is changed using a remotely controlled hydraulic actuator and electric servo system. The rotor control system is a conventional swashplate system which is remotely controlled through the use of three electronic servos and hydraulic actuators. The high frequency response characteristics of this control system are necessary for the higher harmonic inputs.

Instrumentation provisions on the ARES allow continuous measurement of model control settings, rotor forces and moments, blade loads, and pitch link loads. Model pitch attitude is measured by an accelerometer, and rotor control positions are measured by linear potentiometers connected to the swashplate. Rotor blade flapping and lagging are measured by rotary potentiometers mounted on the rotor hub and geared to the blade cuff. The rotating blade data are transferred to the fixed system through a 60-channel, horizontal disk slip-ring assembly. Rotor forces and moments are measured by using a six-component strain-gage balance mounted below the drive system. The balance is fixed with respect to the rotor shaft and pitches with the fuselage. Fuselage forces and moments are not sensed by the balance.

The vibratory forces and moments used as response inputs to the higher harmonic control algorithms were taken from the balance. This means that the moment responses used by the control algorithms were made up of the rotor hub moments plus the rotor inplane shears times the offset distance between the rotor hub and the balance center. This offset distance was 51.44 cm.

(182)

The rotor system used in this investigation was a four-bladed articulared rotor system. The blades were dynamically scaled to be representative of a current generation rotor system. The blades had swept tips consistent with their full-scale counterpart, but the swept tips were not significant with respect to the higher harmonic control program.

The rotor was tested over a range of advance ratios (tunnel speed/rotor tip speed) consistent with the full-scale flight envelope. Because of tunnel limitations, advance ratios below .2 were not possible. The rotor rotational speed was set so as to achieve a full-scale tip Mach number. At each advance ratio the rotor was trimmed to a condition which represented a 1-g flight condition for the full-scale aircraft. Blade flapping was trimmed with respect to the shaft.

DISCUSSION OF RESULTS

The results to be discussed in this section were obtained using the closed loop active control system discussed earlier. In obtaining these results, the model was trimmed at a given advance ratio, and data were recorded to establish the vibratory responses without higher harmonic control. The automatic control system was then turned on and allowed to stabilize. With the controller still on at its stabilized condition, data were recorded to establish the vibratory responses with higher harmonic control. The following results present a comparison with and without higher harmonic control of the vibratory responses, blade loads, and control loads.

The success of the higher harmonic control in reducing the vibratory responses is shown in figures 3, 4, and 5, where the variation of the responses with advance ratio are shown both with and without higher harmonic control. Figure 3 shows the variation of the vibratory vertical force. As may be seen from this figure, the higher harmonic control was quite successful in reducing this vibratory response. Reductions of from 70 to 90 percent were obtained over the range of advance ratios tested. The vibratory pitching moment shown in figure 4 indicates reductions of from 33 to 68 percent and the vibratory rolling moment shown in figure 5 indicates reductions of from 0 to 46 percent.

The fact that the order of the reductions which could be obtained in the vibratory pitching and rolling moments was much less than the reductions obtained in the vertical force is a result for which no explanation has been established. Mathematically, since

(183)

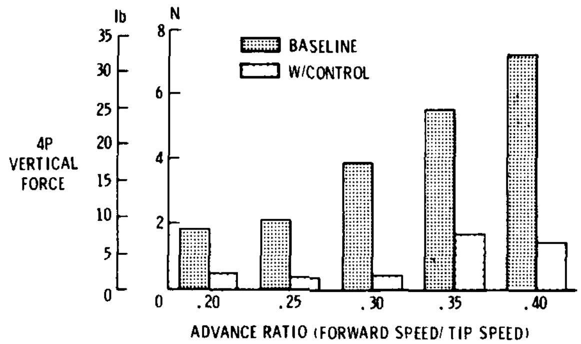


Figure 3. Variation of vibratory vertical force with advance ratio.

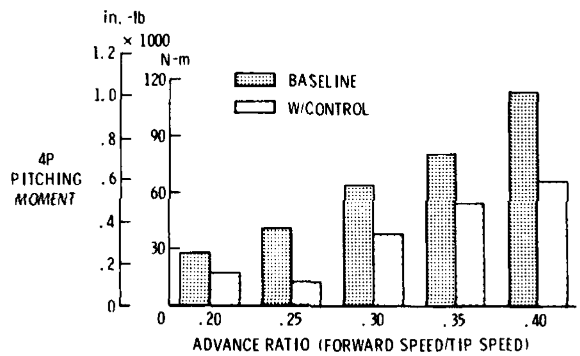


Figure 4. Variation of vibratory pitching moment with advance ratio.

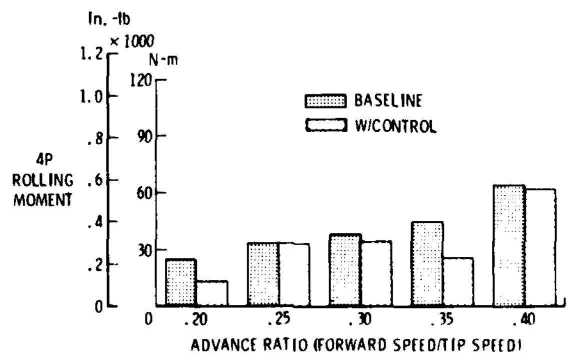


Figure 5. Variation of vibratory rolling moment with advance ratio.

(184)

three inputs were used to control three responses, it should have been possible to drive each of the responses to near zero values. A considerable amount of testing was done to explore this apparent anomaly, but a satisfactory explanation was not found during the wind tunnel test program.

It should be pointed out that the results presented in figures 3-5 were obtained by weighting the vertical force response more heavily than the moment responses (equations (2), (3)). Numerous combinations of the weightings were explored during the test, and it was found that the weightings play a significant role in the levels of vibration reduction which can be obtained. It was found, for example, that with the proper combination of weights, the moments could be reduced more than is shown in figures 4 and 5, but at the expense of less reduction in vertical force.

Efforts to understand why moment response reductions greater than those shown in figures 4 and 5 could not be obtained in conjunction with large reductions in vertical force response are continuing. Indications are that the problem lies in the sensor location, i.e., the moments being sensed by the balance contained hub moment as well as hub shear contributions. Further tests are being performed on the model in a hover facility to reconcile this issue.

It is imperative when evaluating a system which appears to promise high payoff for low investment, e.g., significant vibration reduction with a low weight penalty, that all avenues of possible side effects be explored. In the case of higher harmonic control, since the concept is based on tailoring the blade aerodynamic loads to achieve reductions in the vibratory responses, an examination of the higher harmonic inputs is appropriate. The results to be shown are from the same test points at an advance ratio of .3 as the vibratory responses shown earlier. The results at other advance ratios were similar.

The radial distribution of blade alternating flapwise bending moment (½ peak-to-peak values) is shown in figure 6. Similar distributions for the edgewise moment and torsion are shown in figures 7 and 8, respectively. As may be seen, there is a small reduction in the flapwise bending moment, a significant increase in the edgewise bending moment, and a moderage increase in the torsional moment. With the exception of the edgewise moment, these results are consistent with the open loop results obtained previously (ref. 9).

(185)

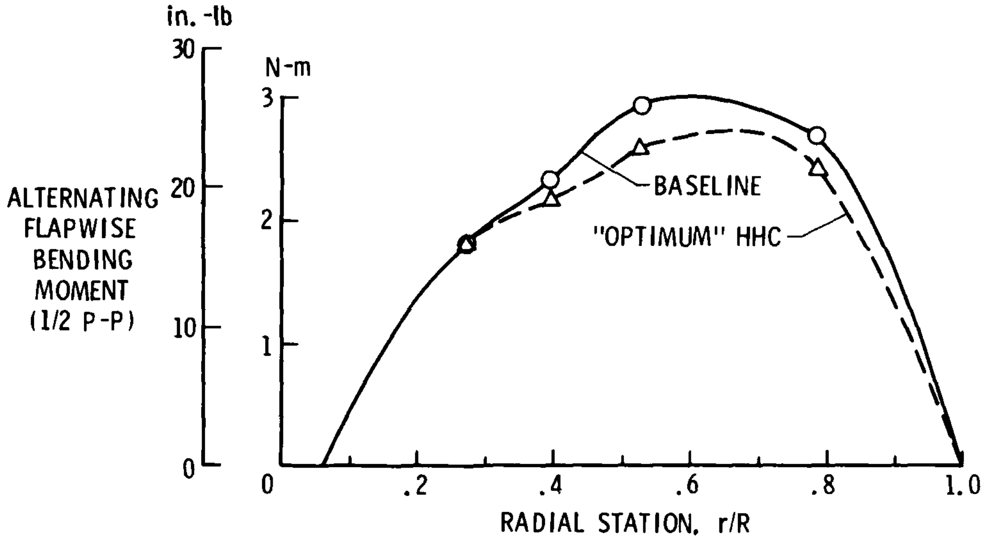


Figure 6. Radial distribution of blade alternating flapwise bending moment (½ peak-to-peak values) at an advance ratio of 0.3.

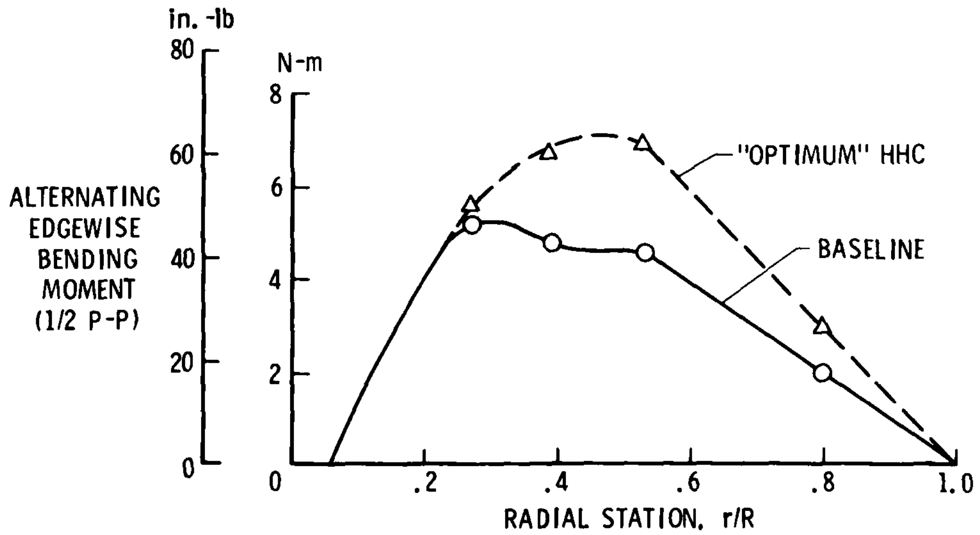


Figure 7. Radial distribution of blade alternating edgewise bending moment (½ peak-to-peak values) at an advance ratio of 0.3.

186

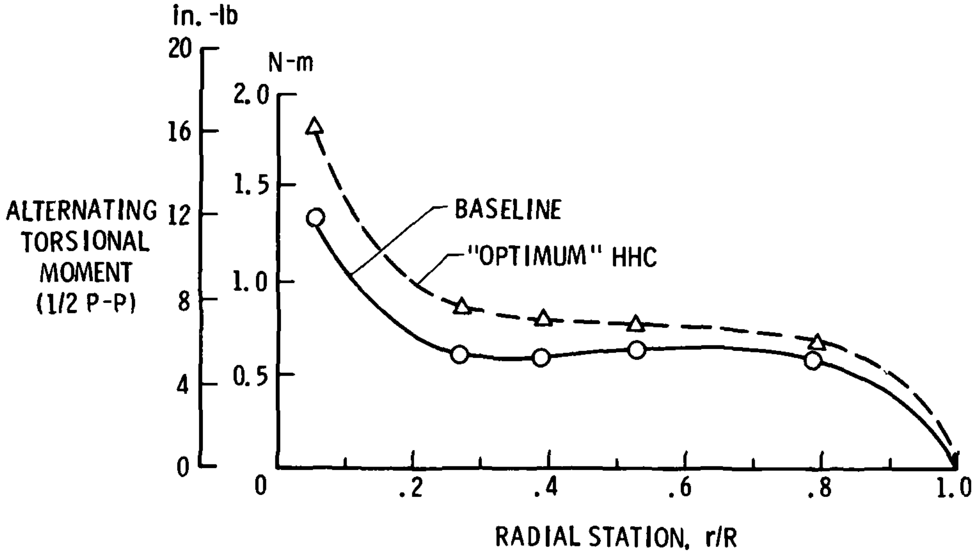


Figure 8. Radial distribution of blade alternating torsional moment (½ peak-to-peak values) at an advance ratio of 0.3.

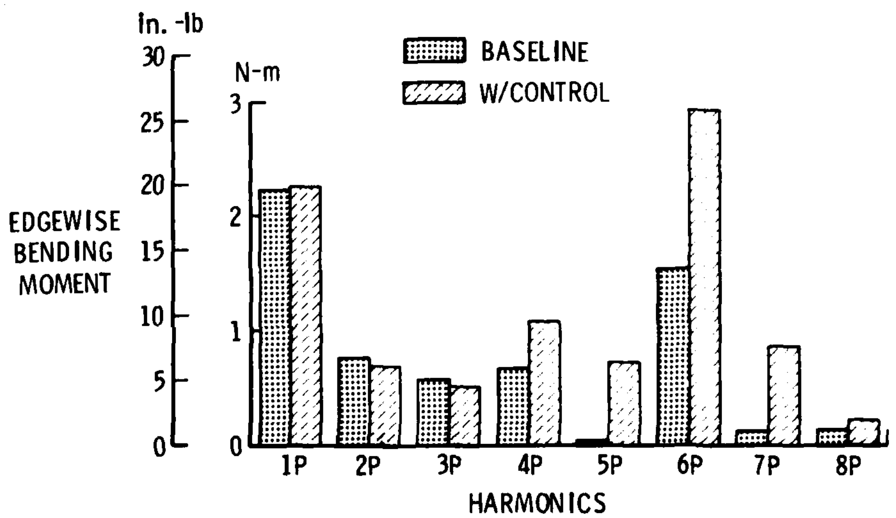


Figure 9. Harmonic decomposition of edgewise bending moment at 53 percent span, and advance ratio of 0.3.

147

The cause of the increase in the edgewise moments appears to be associated with placement of the blade's natural frequencies relative to the rotor harmonics. Figure 9 presents a harmonic decomposition of the edgewise bending moment at 53 percent span. As may be seen, there is a strong contribution at 6P without higher harmonic control, and this contribution is aggravated when higher harmonic control is applied. The strong contribution at 6P without higher harmonic control is indicative of a blade natural frequency near 6P. Excitation of this mode by the higher harmonic control comes from the fact that 4P cyclic motion of the non-rotating swashplate results in 3P and 5P motions of blade pitch in the rotating system, whereas 4P collective motion of the swashplate results in 4P blade pitch changes. Any impurity of the 3P blade pitch motions could excite the 6P natural blade mode since it is a second harmonic of the 3P input.

The indication from the edgewise moments is that if a a new rotor is designed to incorporate higher harmonic control, blade frequency placements subject to constraints imposed bv the higher harmonic control must be a design consideration. Further, for flight testing of higher harmonic control on existing aircraft, the blade loads must be carefully monitored to avoid any excessive stresses. It should be noted that the edgewise loads with higher harmonic control shown in figure 7 are well within the design load envelope for these blades, but the fact that higher harmonic control can produce a significant increase in the loads must be recognized, particularly in flight test programs.

Figure 10 presents the pitch link loads with and without higher harmonic control as a function of advance ratio. As may be seen, and as was expected, there is an increase in the control loads when the higher harmonic control is applied. The source of the increase may be attributed directly to the higher harmonic inputs as may be seen from figure 11. This figure presents a harmonic decomposition of the pitch link load at an advance ratio of .3. Note that the increase in load with higher harmonic input occurs at frequencies of 3P, 4P, and 5P which are the excitation frequencies in the rotating system. These increases in control system loads are consistent with previous findings (ref. 9) and the magnitude of the increases have not caused significant concern among designers. Again, however, these increases must be considered in any flight test program.

188

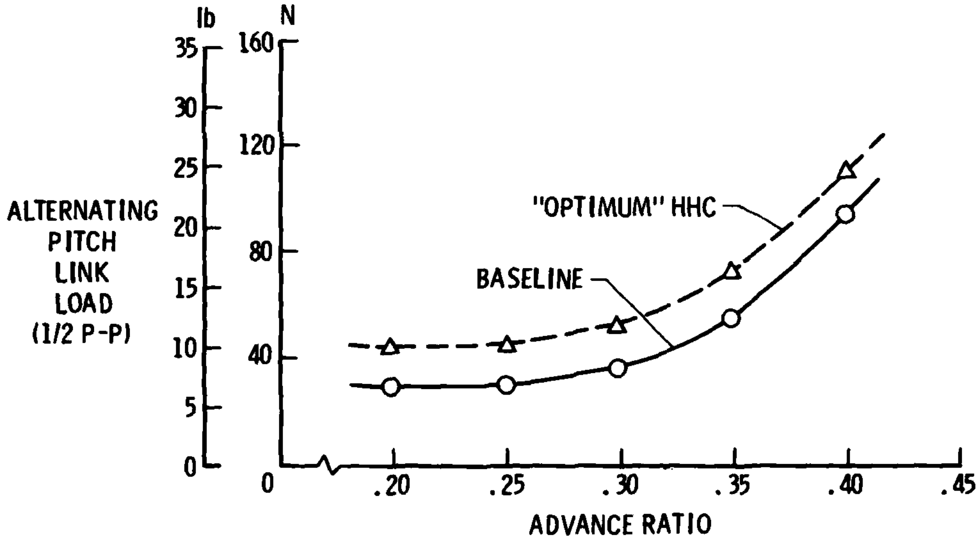


Figure 10. Variation of alternating pitch link load (½ peak-to-peak values) with advance ratio.

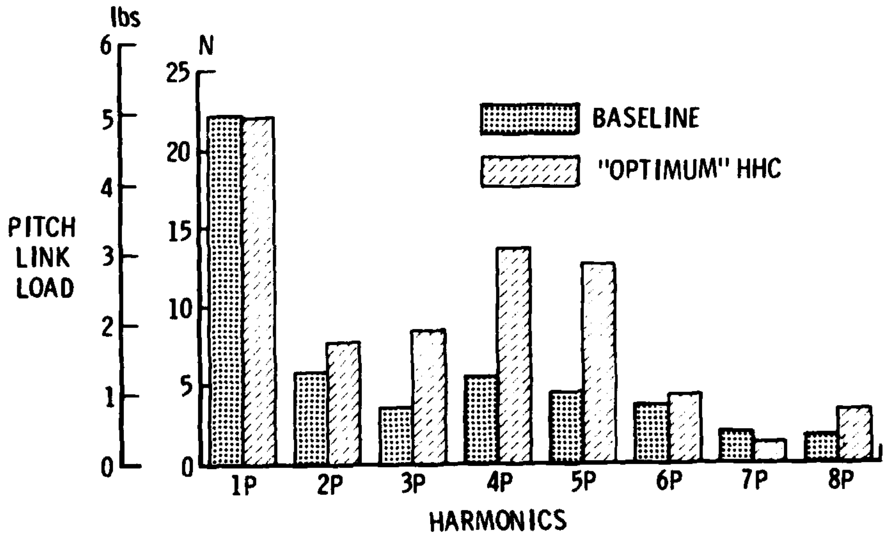


Figure 11. Harmonic decomposition of pitch link load at an advance ratio of 0.3.

(187)

CONCLUDING REMARKS

Results have been presented from a wind tunnel test of a dynamically-scaled helicopter rotor model in which an active control system employing higher harmonic blade pitch was used for helicopter vibration reduction. This test was the first time that an adaptive control system employing optimal control theory has been used for this purpose. The test was successful in that the control algorithms functioned flawlessly and significant reductions in vibratory responses were achieved. An open issue remains, however, as to why even greater reductions in the vibratory responses were not obtained. Further testing is being conducted with the model to resolve this question.

The test results indicate that higher harmonic control can lead to increases in blade and control system loads. For the model tested, increases were evident in the edgewise bending and torsional moments, as well as the pitch link loads. Although the increased loads were considerably below the design limits for the model tested, the fact that blade and control system loads can increase must be considered in any flight test demonstration of the higher harmonic control concept.

Further wind tunnel testing of the active control concept presented in this paper will be conducted in August 1980. Preparations are also underway for a flight test demonstration of the wind-tunnel-developed system. The flight tests will be conducted under contract by Hughes Helicopters using an OH-6A helicopter early in 1981.

REFERENCES

1. Desjardins, R. A., and Hooper, W. E.: Rotor Isolation of the Hingeless Rotor BO-105 and YUH-61 Helicopters. Second European Rotorcraft and Powered Lift Aircraft Forum, Paper No. 13, Sept. 1976.

2. Ricks, R. G., and Gabel, R.: Vibration Optimization of the CH-47C Helicopter Using NASTRAN. Symposium on Mathematical Modeling in Structural Engineering, Langley Research Center, Oct. 1979.

3. Amer, K. B., and Neff, J. R.: Vertical Plane Pendulum Absorbers for Minimizing Helicopter Vibratory Loads. J. American Helicopter Society, Vol. 19, No. 4, Oct. 1974, pp. 44-58.

(190)

4. Paul, W. F.: Development and Evaluation of the Main Rotor Bifilar Absorber. Proceedings of the 25th Annual National Forum, American Helicopter Society, May 1969.

5. Flannelly, W. G.: The Dynamic Antiresonant Vibration Isolator. Proceedings of the 22nd Annual National Forum, American Helicopter Society, May 1966.

6. Wood, E. R., and Powers, R. W.: Practical Design Considerations for a Flightworthy Higher Harmonic Control System. Proceedings of AIAA/ASME/ASCE/AHS 21st Structures, Structural Dynamics, and Materials Conference, May 1980.

7. Sissingh, G. J., and Donham, R. E.: Hingeless Rotor Theory and Experiment on Vibration Reduction by Periodic Variation of Conventional Controls. Rotorcraft Dynamics, NASA SP-352, February 1974.

8. McHugh, F. J., and Shaw, J., Jr.: Benefits of Higher Harmonic Blade Pitch: Vibration Reduction, Blade-Load Reduction and Performance Improvement. Proceedings of the Aermican Helicopter Society Mideast Region Symposium on Rotor Technology, August 1976.

9. Hammond, C. E.: Helicopter Vibration Reduction Via Higher Harmonic Control. Proceedings of the Rotorcraft Vibration Workshop, NASA Ames Research Center, February 22-23, 1978.

10. Bryson, A. E., Jr., and Ho, Y. C.: Applied Optimal Control. John Wiley & Sons, 1975.

11. Goodwin, G. C., and Payne, R. L.: Dynamic System Identification: Experiment Design and Data Analysis. Academic Press, 1977.

12. Hammond, C. E., and Weller, W. H.: Wind-Tunnel Testing of Aeroelastically Scaled Helicopter Rotor Models (U). 1976 Army Science Conference, West Point, NY, June 22-25, 1976.

13. vonDoenhoff, A. E., Braslow, A. L., and Swartzberg, M. A.: Studies of the Use of Freon-12 as a Wind Tunnel Testing Medium. NACA TN-3000, 1958.

14. Hammond, C. E., and Weller, W. H.: Recent Experience in the Testing of a Generalized Rotor Aeroelastic Model at Langley Research Center. Second European Rotorcraft and Powered Lift Aircraft Forum, Paper No. 35, Sept. 1976.

(191)